Model of Rock Drilling Process in Terms of Roller Cone Bit Remaining Life

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Abstract
The issue of the absence of any formalized methods showing nonlinear dependence of the drilling rate on the drilling rod assembly speed has been revealed. The peculiarities, influencing the greatest number of cycles prior to the destruction of bit legs, have been defined. The results of an investigation into the process of impact load harmonics formation and superposition, as well as into the interrelation of drilling process parameters in different loading conditions, with due regard for an adaptive element smoothing the impact load harmonics when passing through rock of different drillability indices, have been adduced. It has been determined that an adaptive element is required for ensuring timely system response to the exposed object properties change, as well as for maintaining the optimum ratio of model parameters in the course of its operation. The approach to determining the roller cone bit speed, at which the bit teeth contact time will be sufficient for energy transfer, resulting in the required rock volume cutting, has been defined. The conditions for rock cutting maximum efficiency have been found. The effective way of reducing temporary and cyclic loads on specific bearing rolling elements and teeth has been determined. The procedure for calculating the optimum roller cone bit speed, maximum permissible feeding force and tri-cone bit life in the course of drilling rock masses of different stress-strain properties has been developed.

Keywords: operating parameters, roller cone bit, adaptive element, drilling rate, life, uncertainty.

INTRODUCTION

Nowadays there is no methodology for building, analyzing and evaluating the model of rock drilling process in terms of roller cone bit remaining life with regard for an adaptive element under the conditions of insufficient information about rock stress-strain properties change, which constitutes an important scientific challenge crucial to mining industry.

The selection of the model describing the performance indicators of the whole system based on the studied peculiarities and the nature of its operation parameters interrelation presents the most responsible and complicated modeling stage [1-4].

Developing calculation methods, studying the peculiarities and estimating interrelations between the drilling process model parameters, with regard for an adaptive element in the system, enables to significantly reduce the time required for determining static and dynamic object characteristics, as well as to comprehensively evaluate their field of application and future states of the technical system under study, to improve the accuracy of defining and maintaining the optimum operating parameters in the conditions of uncertainty [5]. Thus, the solution of the above issues will contribute to the improvement of rock drilling process efficiency.

METHODS

Work on rock cutting:

Today, there exist a great number of methods intended for evaluating roller bit drilling rigs capacity [6-9]. However, there are no adequately formalized methods which would uniquely show nonlinear dependence of the drilling rate on the drilling rod assembly rotation speed. The experimental and test data show clearly that the drilling rate increases almost linearly up to a certain point, but its growth stops gradually [10]. This can be explained on the following basis. The roller cone bit operating principle includes the mechanism of specific teeth cyclic impact on the bottomhole. The rock is characterized by a range of physical and mechanical properties which, from the point of view of cutting mechanics, can be divided into two groups: structure characteristics and strength characteristics. In a specific point of rock mass, the rock is characterized by a certain set of properties which determine some scope of work to be performed by the drilling rig through the application of the next roller bit tooth in order to break up a certain volume of this rock [11]. At the same time, the drilling rig operating mechanism has a definite power which should be imposed on the rock volume within a certain period of time in order to break it having performed the work:

$$A_{\text{cut}} = N \cdot t_{\text{cut}},$$

where t_{cut} – time required for cutting a certain volume of rock with one roller bit tooth;
N – power of the drilling rig operating mechanism which is transferred with a drilling tool for rock cutting.

The power shall be determined using the following formula:

$$N = P_{\text{ax}} v_{\text{d}},$$

where P_{ax} – axial force; v_{d} – drilling rate.

As a rule, roller cone bits are effectively operated when drilling hard though brittle rock. In case of significant material elasticity, the share of energy loss due to the deformation and its further transformation into heat will be significant. However, in case Protodiakonov hardness value exceeds 6, rocks are mostly not characterized by significant elasticity and enable roller cone bit operation in the mode of rock brittle cutting.

Under the given conditions, according to A.A. Tsuprikov [12], the drilling rate, without regard to energy loss due to rock deformation and heat release, can be determined from the expression:

$$v_d = \frac{8n_{\text{rot}} \cdot P_{\text{ax}} \cdot k_{\text{roller bit}}}{D_1^2 \cdot \sigma_{\text{surf}} \cdot k_{\text{vol.destr}}},$$

where n_{rot} – roller cone bit rotation speed, s^{-1};

D_1 – bit diameter, m;

P_{ax} – axial force, N;

$k_{\text{roller bit}}$ – proportionality factor, equal to the roller cone bit radius, m;

$k_{\text{vol.destr}}$ – volumetric destruction factor which characterizes the destruction of rock, its ability for being cut into pieces, even to powder state;

σ_{surf} – surface density of the rock material free energy N/m^2.

$\sigma_{\text{surf}} = \frac{F_{cut}}{S \cdot k_{vol.destr}}$, where F_{cut} – force of structural cutting of the rock, N; S – area of the cut rock cross section, m^2.

The physical sense of σ_{surf} value complies with the material tensile strength with regard for the existing damages.

According to R.Yu. Poderni [13], the drilling rate can be calculated from the expression:

$$v_d = \frac{40P_{\text{ax}} \cdot n_{rot}}{I_{\text{d}} \cdot D_1^2}, \text{ m/h},$$

where P_{ax} – axial force, MN; n_{rot} – drilling rod assembly rotation speed, s^{-1};

I_{d} – drillability index, $I_d = 0.07 \cdot (\sigma_{compr} + \sigma_{shear}) + 0.7\gamma$, where $\sigma_{\text{compr.}}$ – rock ultimate strength at uniaxial compression, MPa; σ_{shear} – rock ultimate shear strength, MPa; γ – rock density, t/m^3.

The drillability index I_d is determined from the following expression:

$$I_{\text{d}} = \frac{\sigma_{\text{surf}} \cdot k_{\text{vol.destr.}}}{7.2 \cdot 10^8 k_{\text{roller bit}}}, \qquad (1)$$

Based on the brittle cutting condition, single tooth action [12]:

$$A_{\text{cut}} = V_{\text{cut}} \sigma_{\text{surf}} \cdot k_{\text{vol.destr}},$$

where V_{cut} – volume of rock cut by a single tooth as a result of a single action, m^3.

As this takes place, the maximum volume of rock is limited by the size of a single tooth protruding part h in the roller bit gear train, the distance between teeth of one gear train, as well as the distance between the roller bit gear trains.

Conditions for drilling process optimization:

The time period required for rock cutting A_{cut} with the roller bit single tooth at the drilling rig operating mechanism power N can be determined from the following expression:

$$t_{\text{cut}} = \frac{A_{\text{cut}}}{N} = \frac{V_{\text{cut.}} \cdot \sigma_{\text{surf}} \cdot k_{\text{vol.destr.}}}{v \cdot P_{\text{ax}}},$$

Taking into account expression (1), we get:

$$t_{\text{cut}} = 7.2 \cdot 10^8 \frac{k_{\text{roller bit}} \cdot \mathrm{I_d} \cdot V_{\text{cut.}}}{N} \text{ or}$$

$$t_{\text{cut}} = 7.2 \cdot 10^8 \frac{k_{\text{roller bit}} \cdot \mathrm{I_d} \cdot V_{\text{cut.}}}{v \cdot P_{\text{ax}}},$$

In order to determine the roller bit rotation speed, at which the teeth contact period will be sufficient for transferring the energy resulting in the required rock volume cutting, the time of this rock volume cutting shall be compared with the teeth-rock contact period under the given kinematic laws of motion, with account of roller bit diameter and the number of teeth per gear train. Then the period of tooth contact shall be determined as follows:

$$t_{\text{t.c}} = \frac{1}{n_{\text{rot}} \cdot \frac{D_1}{D_{\text{roller bit}}^{\max}} \cdot k},$$

where $D_{\text{roller bit}}^{\max}$ – maximum roller bit diameter;

k – number of teeth in all gear trains of the roller bit.

For tri-cone bits:

$$t_{\text{t.c.}} = \frac{1}{1.7 \cdot n_{\text{rot}} \cdot k}.$$

Maximum cutting efficiency corresponds with the equation:

$$t_{\text{t.c.}} = t_{\text{cut.}}$$

If $t_{\text{t.c.}} > t_{\text{cut.}}$, the drilling rig operating time is not spent effectively and the drilling rod assembly speed shall be increased. If $t_{\text{t.c}} < t_{\text{cut.}}$, the drilling tool life is not consumed effectively and the rotation speed shall be reduced. Therefore, in order to ensure the efficient operation of the roller cone bit, one should strive for fulfilling the following condition:

$$k_{\text{eff. rot}} = \frac{t_{\text{cut}}}{t_{\text{t.c.}}} = 7.2 \cdot 10^8 \cdot n_{\text{rot}} \cdot k \frac{k_{\text{roller bit}} \cdot \mathrm{I_d} \cdot V_{\text{cut}}}{v \cdot P_{\text{ax}}} \cdot \frac{D_1}{D_{\text{roller bit}}^{\max}} = 1,$$

where $k_{\text{eff.rot}}$ – efficiency factor for roller cone bit drilling depending on the rotation speed.

For tri-cone bits:

$$k_{\text{eff.rot}} = \frac{t_{\text{cut}}}{t_{\text{t.c.}}} = 7.2 \cdot 10^8 \cdot 1.7 \cdot n_{\text{rot}} \cdot k \cdot \frac{k_{\text{roller bit}} \cdot \mathrm{I_d} \cdot V_{\text{cut}}}{v \cdot P_{\text{ax}}} = 1$$

From the condition of roller cone bit maximum efficiency it follows:

$$\frac{1}{1.7 \cdot n_{\text{rot}} \cdot k} = 7.2 \cdot 10^8 \frac{k_{\text{roller bit}} \cdot \mathrm{I_d} \cdot V_{\text{cut}}}{v \cdot P_{\text{ax}}}$$

The tri-cone bit maximum rotation speed is determined from the expression:

$$n_{\text{rot}} = \frac{N}{12.24 \cdot 10^{8} \cdot k \cdot k_{\text{roller bit}} \cdot \text{I}_{\text{d}} \cdot V_{\text{cut}}}, \quad \text{or}$$

$$n_{\text{rot}} = \frac{N}{D_{1} \cdot 3.6 \cdot 10^{8} \cdot k \cdot \text{I}_{\text{d}} \cdot V_{\text{cut}}}.$$

In case of one complete revolution of a roller bit and bottomhole coverage with all its teeth, the maximum bit rotation speed in the course of rock mass drilling shall be determined from the following expression:

$$n_{\text{rot}} = \frac{0.94 \cdot N}{10^{8} \cdot \pi \cdot D_{1}^{3} \cdot \text{I}_{\text{d}} \cdot h}, \tag{2}$$

where h – height of the tooth protruding from the gear ring, m.

When drilling a rock mass of complex structure, bit passing through various discontinuities and dehomogenizations is accompanied by serious non-process impacts and vibration. As a result, the bit life is reduced by two-fold or even more. The natural physical means of reducing reactive loads on specific bearing rolling elements and teeth involves decreasing the amount of energy transferred to this spot of material or rock. This technique is effective in respect of temporary and cyclic loads. For a roller bit, rolling over from tooth to tooth, the evident implementation of this technique is presented by the increase in the roller cone bit rotation speed. Thus, in the event a crevassed rock is drilled, the rotation speed obtained from expression (2) shall be increased by the value dependent on the degree of loads increase due to the impacts which take place when passing through crevices or other rock mass discontinuities and dehomogenizations.

The stress in the rolling contact bearing roller of the roller cone bits can be calculated from the expression:

$$\sigma_{\text{i.l.r.}}^{\Sigma} = 600 \cdot \sqrt[3]{\frac{F_r}{z \cdot D_{\text{r}} \cdot L_{\text{r}}}} \cdot \frac{2(v_{\text{d}} + v_s/2)}{2(v_{\text{d}} + v_s/2) - v_s/2} \cdot \frac{2\text{I}_{\text{d}}^{1} + 2\Delta\text{I}_{\text{d}}}{2\text{I}_{\text{d}}^{1} + \Delta\text{I}_{\text{d}}} \cdot k_{\text{ind}}, \tag{3}$$

where

F_{r} – radial force applied to a bearing, N;

z – number of rolling elements in a bearing;

D_{r} – roller diameter, mm;

L_{r} – roller length, mm;

v_{s} – roller bit tooth decent speed, m/s;

ΔI_{d} – change of rock mass drillability index under strength characteristics change, discontinuity and dehomogenizations;

k_{ind} – indenter geometry shape factor.

Optimum modes:

Miscellaneous criteria are used in mathematical statement of the problem of optimizing the roller bit drilling process [5]. Taking into account expression (3), the optimum rotation speed in the course of complex rock mass drilling can be calculated using the following formula:

$$[n_{\text{rot}}] = \frac{0.94 \cdot N}{10^{8} \cdot \pi \cdot D_{1}^{3} \cdot I_{\text{d}} \cdot h} \cdot \frac{2\text{I}_{\text{d}}^{1} + 2\Delta\text{I}_{\text{d}}}{2\text{I}_{\text{d}}^{1} + \Delta\text{I}_{\text{d}}} \cdot k_{\text{ind}}, \tag{4}$$

As is clear from expression (16), the rotation speed in the course of rock mass drilling depends on the change of its strength characteristics, discontinuity and dehomogenization. As this takes place, with the increase of difference in strength characteristics, crevassing and bedding, the optimum rotation speed is growing, thus reducing the general load on specific roller cone bit rolling elements. The optimum rotation speed can be structurally reduced by lowering the indenter factor k_{ind} due to the bigger angle of throat of the roller bit teeth and bit diameter increase. The rock characterized by higher average drillability index shall be also drilled at lower rotation speed as compared with the rock characterized by lower hardness.

The maximum permissible feeding force of the drilling rig operating mechanism shall be determined based on the permissible loads imposed on the roller cone bit rolling elements. Taking into account expression (3), the permissible maximum feeding force in the course of drilling rock masses, possessing different physical and mechanical characteristics, can be calculated as follows:

$$[P_{\text{ax}}] = 6 \cdot z \cdot D_{\text{r}} \cdot L_{\text{r}} \cdot \left(\frac{[\sigma_{\text{i.l.r.}}]}{600 \frac{2(v_{\text{d}} + v_{\text{s}}/2)}{2(v_{\text{d}} + v_{\text{s}}/2) - v_{\text{s}}/2} \cdot \frac{2\text{I}_{\text{d}}^{1} + 2\Delta\text{I}_{\text{d}}}{2\text{I}_{\text{d}}^{1} + \Delta\text{I}_{\text{d}}} \cdot k_{\text{ind}}} \right)^{3}, \tag{5}$$

where $[\sigma_{\text{i.l.r.}}]$ – permissible stress of the roller cone bit rolling elements material.

It follows from expression (5) that, in the course of rock mass drilling, the feeding force depends on the change of strength characteristics, discontinuity and dehomogenization. As this takes place, with the increase of difference in strength characteristics, crevassing and bedding, the optimum force value is decreasing, thus reducing the general load on specific roller cone bit rolling elements. The optimum force value can be structurally enhanced by increasing the number and dimensions of the roller cone bit rolling elements, as well as by lowering the indenter factor k_{ind} due to the bigger angle of throat of the roller bit teeth. Besides, the optimum value of the operating mechanism feeding force can be enhanced due to the increase in the tensile strength for the roller cone bit rolling elements material.

The rock mass properties change directly in the process of well drilling [14-16]. Therefore, the maximum permissible feeding force of the drilling rig operating mechanism becomes a variable value. As the bit penetration increases, the maximum permissible feeding force changes in accordance with the change of the drillability index and rock mass structure. It is near-impossible to eliminate instantaneous loads in modern drilling rigs, both of home and foreign manufacture. And it is afterwards when the operator responds to the rock properties change. That is why, in order to prevent the destruction of roller cone bit legs due to a single impact, the operator shall preliminarily set a lower feeding force. The lower feeding force value shall be determined based on the operator's personal experience. This value is always lower than the value which can be determined using expression (3).

Process of instantaneous load formation:
Instantaneous loads are complex phenomena which have a significant effect on the drilling tool life [17, 18]. The electromagnetic linear drive smoothens all instantaneous load harmonics lasting for more than 0.01 s, when the bit passes through crevices and boundary areas of the rock characterized by different hardness. In the event a linear three-phase motor with 50 Hz mains frequency is used as an adaptive feeding mechanism of the drilling rig, the harmonics lasting longer than 0.01 s brought about by instantaneous loads are smoothened.

The process of harmonics formation and superposition is shown in Figure 1.

The smoothened harmonic amplitude depends on the time of impact pulse propagation from the tooth-rock contact point to the roller bit rolling elements surface [19]:

$$t = \frac{2l}{\sqrt{\frac{E}{\rho}}},$$

where l – path covered by the impact pulse, m;
E – module of material elasticity along which the impact pulse is propagated, Pa;
ρ – density of the material along which the impact pulse is propagated, kg/m^3.

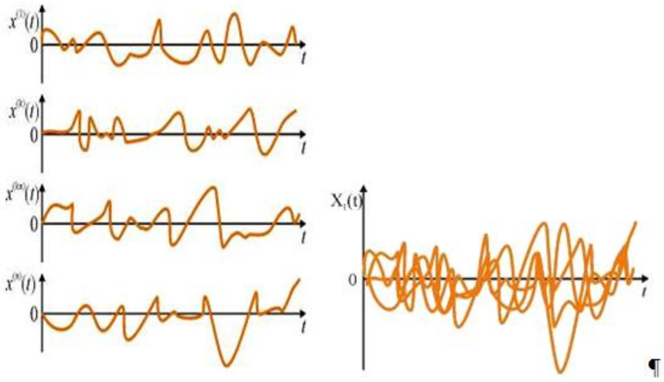

Figure 1. Formation and superposition of instantaneous load harmonics in the course of drilling

On a certain scale, the impact wave can be presented as a circle segment, as shown in Figure 2. Then, the relative value of W power, transformed into mechanical energy at the given moment, can be laid off as ordinate. And the power integral for t period is equal to the relative value of the work or power which is mostly applied for destroying the bit rolling contact bearing. This work can be presented as a figure area limited by a circle arc with O center, R radius and t chord lying on the abscissa axis.

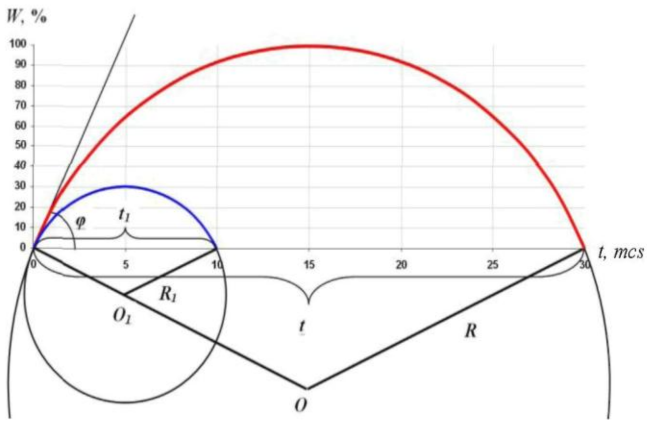

Figure 2. Propagation and smoothing of impact wave upon its duration for over 0.01 s

The energy is absorbed by the electromagnetic coupling and the impact wave is smoothed within 10 ms. Thus, the power transformed into mechanical energy is shown in Figure 2 as a figure area limited by a circle arc with O center, R radius and t chord lying on the abscissa axis. φ angle formed by the line tangent to the arcs coming from the origin of coordinates, and the abscissa axis is similar for both cases described, as at the initial instant $t = 0$ the impact wave power depends only on the force, feeding speed and the properties of the affected object. From here it follows that the expression for the relative value of the impact wave energy with no adaptive element is as follows:

$$E_{sh} = \frac{t^2}{8 \cdot (\sin\varphi)^2} \cdot \left(\frac{\pi \cdot \varphi}{90} - \sin 2\varphi \right),$$

where E_{sh} – relative value of the impact wave energy appearing upon the drilling tool contact with the rock;
t – time of the impact wave propagation without an adaptive element, ms.

The expression for the relative value of the impact wave energy with an adaptive element:

$$E_{sh}^{a} = \frac{t_1^2}{8 \cdot (\sin\varphi)^2} \cdot \left(\frac{\pi \cdot \varphi}{90} - \sin 2\varphi \right),$$

where t_1 – time of the impact wave propagation with an adaptive element, ms.

Therefore, when the operating mechanism is fed by the adaptive element, the maximum permissible feeding force shall be determined based on the loads permissible for bit elements, as well as the relation of the impact wave energy with an adaptive element and without it. This element allows making the best use of random disturbances which, in the absence of any control, can result in non-efficient energy consumption and decrease system life.

Based on the afore-referenced expressions, the impact component of expression (3) will be lessened. The stress in the rolling elements can be calculated as follows:

$$\sigma^{\Sigma}_{i.l.r(ad)} = 600 \cdot \sqrt[3]{\frac{F_r}{z \cdot D_r \cdot L_r}} \cdot \left(\left(\frac{2(v_d + v_s/2)}{2(v_d + v_s/2) - v_s/2} \cdot \frac{2I_d^1 + 2\Delta I_d}{2I_d^1 + \Delta I_d} - 2 \right) \cdot \frac{t_1^2}{t^2} + 2 \right) \cdot k_{ind}$$

In case an adaptive feeding drive is applied and drilling is performed with the use of a hard alloy press-fit teeth tri-cone bit, the maximum permissible feeding force can be increased by 30-35%. In the event drilling is performed with the use of a milled-teeth bit, this parameter can be increased by 35-40% due to an extended tooth protrusion. The drilling rate can be increased by approximately the same value, in the event an adaptive electric drive is applied to the rigs equipped with solid hydraulic drives feeding operating mechanism.

Bit life :

The presented expressions used for calculating stresses help determine the number of cycles before the destruction of elements under different loading conditions:

1. Drilling homogeneous rock with approximately similar properties or drillability index change within $\Delta I_d < 1$. The process is accompanied only by cyclic load with maximum stresses appearing in the elements of the structure with regard for the indenter geometry shape factor k_{ind}.
2. Drilling of bedded rock is characterized by serious impact loads. In order to determine the number of loading cycles when crossing the boundary between the rock beds possessing different physical and mechanical properties, one should take into account the number of rock beds per running meter. This index value ranges from 0 to 20 and more.
3. Drilling of crevassed rock is characterized by significant impact loads. The number of crevices per running meter of a well ranges approximately within 0 to 20. However, the expression determining the bit life, when drilling bedded and crevassed rock, should consider the absolute value of the number of crevices and beds. Under these load conditions the structure elements undergo total cyclic load.

The maximum stresses for the second and the third loading conditions can be found from expression (3). It can be conventionally assumed that at the given moment the drillability index descends to zero and rises to the previous value. While crossing the boundary between the beds is accompanied by a hike in the drillability index $\Delta I_d < I_d$.

To determine the bit life characterized by all three loading conditions, one should determine the shares of the total number of loading cycles of bit elements, which account for drilling homogeneous [ita]$_h$, bedded [ita]$_{r.l}$ and crevassed rock [ita]$_{cr}$ respectively:

$$\eta_h = 1 - \eta_{r.l} - \eta_{cr}; \quad \eta_{r.l} = \frac{n_{r.l} \cdot n_t^{r.l}}{n_{rot} \cdot \frac{D_1}{D_r^{max}}} \cdot v_d; \quad \eta_{cr} = \frac{n_{cr} \cdot n_t^{cr}}{n_{rot} \cdot \frac{D_1}{D_r^{max}}} \cdot v_d$$

where $n_{r.l}$ – number of boundaries between rock beds possessing different physical and mechanical properties per running meter, m^{-1};
n_{cr} – number of crevices in the rock per running meter, m^{-1};
$n_t^{r.l}$ – number of bit revolutions required for passing through the boundary between rock beds;
n_t^{cr} – number of bit revolutions required for passing through the rock mass crevices;
n_{rot} – rotation speed of the roller cone bit, rpm.

The number of bit revolutions required for passing through the boundary between the beds or through the rock mass crevice is determined from the following expressions:

$$n_t^{r.l} = \delta_{r.l} \cdot \frac{n_{rot}}{v_d}; \quad n_t^{cr} = \delta_{cr} \cdot \frac{n_{rot}}{v_d},$$

where
$\delta_{r.l}$ – thickness of the boundary bed or its size, m;
δ_{cr} – thickness of the crevice or its size, m.

As a result of a complex cyclic loading, the legs of the roller cone bit rolling elements withstand a certain number of loading cycles [20]. Such peculiarities as bearing type, its tightness, availability of a shirttail, choice of the material of rolling elements and other elements can structurally effect the greater part of cycles before the bit leg breakage.

For rolling elements, the bearing life, with regard for cyclic load, can be determined as follows [20]:

$$L = 10^6 \cdot \left(\frac{\sigma_u}{\sigma_{max}} \right)^{10/3} \cdot \frac{\sigma_{-1}}{\sigma_a + \frac{\sigma_{-1}}{\sigma_u} \cdot \sigma_m}, \qquad (6)$$

where
σ_u – ultimate tensile strength of the material, MPa;
σ_{max} – peak impact stress, MPa;
σ_{-1} – fatigue strength of the material, MPa;
σ_a – amplitude of the cycle variable stresses, MPa;
σ_m – mean cycle stress, MPa.

In order to ensure a deeper bit penetration at similar drilling rig operating parameters, it is important to select the roller bit cutting structure correctly. The peculiarities of the cutting structure include material, roller bit teeth pattern, relative location of gear rings, the density of their location in each gear train, teeth protrusion from the roller bit body.

Tri-cone bit life with regard for expression (6):

$$T = \frac{L}{2 \cdot n_{rot} \cdot 1.7} \cdot v_d, \text{ m.} \qquad (7)$$

With regard for the expressions used to determine optimum operating parameters (4) and (5), the drilling rate under optimum control, with an adaptive element applied, shall be determined as follows:

$$v_d = \frac{40\,[P_{ax}] \cdot [n_{rot}]}{I_d \cdot D_1^2}.$$

RESULTS

Using the developed methods, there have been built several dependencies for the rocks which differ significantly in terms of crevassing and bedding (Figure 3).

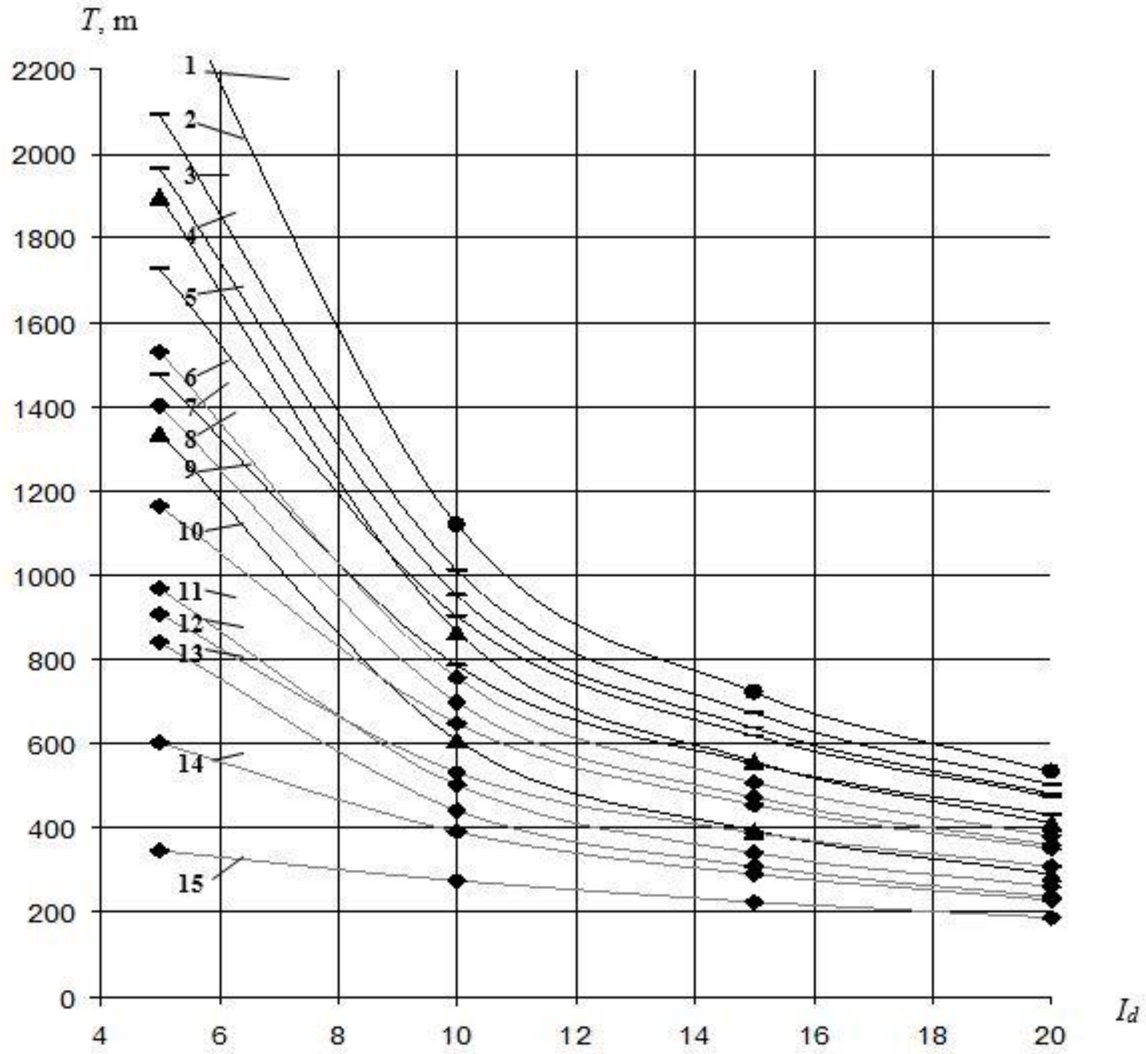

Figure 3. Roller cone bit life depending on the drillability index I_d for homogeneous, bedded, crevassed and bedded-and crevassed rock

Here:

● – dependence for homogeneous rock (Curve 1);

▬ – dependencies for bedded rocks. Curve 2 has been obtained for the following rock characteristics: number of rock beds per running meter of the well $n_{bed} = 10\ m^{-1}$; mean difference of the drillability index for the adjacent beds in the rock mass $\Delta D_f = 2$. Curve 3 has been obtained at $n_{bed} = 10\ m^{-1}$, $\Delta D_f = 4$; Curve 5 – at $n_{bed} = 20\ m^{-1}$, $\Delta D_f = 2$; Curve 7 – at $n_{bed} = 20\ m^{-1}$, $\Delta D_f = 4$;

▲ – dependencies for crevassed rocks. Curve 4 has been obtained at the number of crevices per running meter $n_{fr} = 10\ m^{-1}$; Curve 9 – at $n_{fr} = 20\ m^{-1}$;

♦ – dependencies for rock masses characterized by both bedding and crevassing, Curve 6 has been built at $n_{fr} = 10\ m^{-1}$, $n_{bed} = 10\ m^{-1}$ and $\Delta D_f = 2$; Curve 8 – at $n_{fr} = 10\ m^{-1}$, $n_{bed} = 10\ m^{-1}$ and $\Delta D_f = 4$; Curve 10 – at $n_{fr} = 10\ m^{-1}$, $n_{bed} = 20\ m^{-1}$ and $\Delta D_f = 2$; Curve 11 – at $n_{fr} = 20\ m^{-1}$, $n_{bed} = 10\ m^{-1}$ and $\Delta D_f = 2$; Curve 12 – at $n_{fr} = 10\ m^{-1}$, $n_{bed} = 20\ m^{-1}$ and $\Delta D_f = 4$; Curve 13 – at $n_{fr} = 20\ m^{-1}$, $n_{bed} = 10\ m^{-1}$ and $\Delta D_f = 4$; Curve 14 – at $n_{fr} = 20\ m^{-1}$, $n_{fr} = 20\ m^{-1}$ and $\Delta D_f = 2$; Curve 15 – at $n_{fr} = 20\ m^{-1}$, $n_{bed} = 20\ m^{-1}$ and $\Delta D_f = 4$.

The developed methods for determining roller cone bit life require allowing for feeding force, drilling rod assembly rotation speed, mechanical properties of the steel of the rolling elements of roller bit legs, as well as the size of the crevice and boundary beds along the drilling rod assembly axis. For instance, the dependencies shown in Figure 3 have been obtained at 200 kN feeding force, 1.5 rpm rotation speed, and at 10 mm size of the crevice and boundary beds along the axis of the drilling rod assembly.

DISCUSSION

The developed methods are quite easy to use and are intended for determining the predicted life of the roller cone bits of

various types and dimensions in the course of their operation in the conditions of rock drilling characterized by different degree of bedding and crevassing. Under these conditions, it is appropriate to perform multiple-parameter calculations with the help of specially designed software. This software can show the remaining predicted life for the roller cone bit under this or that drilling rig operating mode. As this takes place, the operator shall be provided with the possibility of continual monitoring the efficiency of the machine operation, as well as tracking the correlation between the feeding force, rotation speed, drilling rate and the remaining predicted life.
Figure 4 shows the calculated dependencies of the specific expenditures on rock drilling with different operating parameters. The calculated dependencies with account of the expressions intended for determining optimum operating parameters (4) and (5) allow determining minimum specific expenditures under the optimum control conditions. Figure 4 shows a point corresponding with the optimum operating parameters [P_{ax}], [n_{rot}] and the maximum efficiency of the drilling process as per the integrated index. The classical method used for the evaluation of the drilling process efficiency is not related to the operating parameters optimization and handles aposteriori information about the existing performance indicators. In this case, the analysis of the obtained information, sufficient for statistical processing, allows making conclusions about the correction of the drilling process modes with the aim to improve the indicators of reliability, performance and cost.

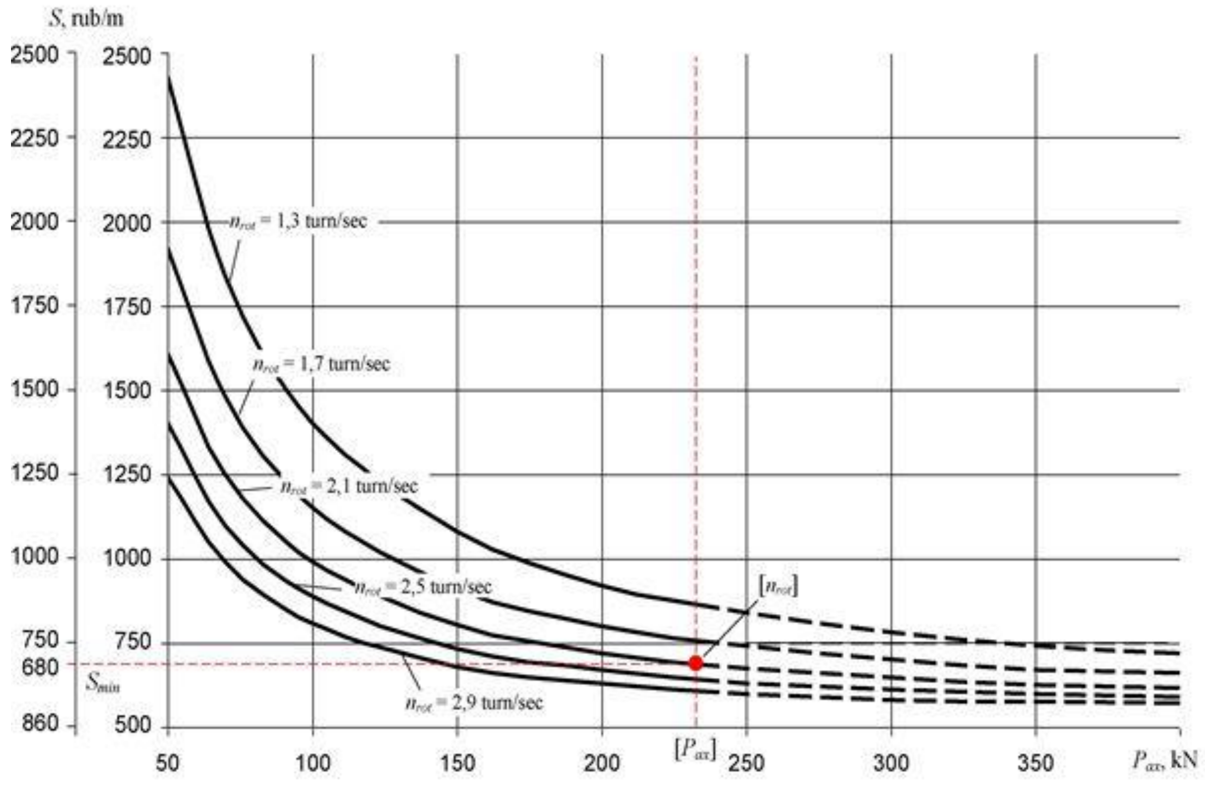

Figure 4. Dependencies of the integrating efficiency indicator of the drilling process performance on the operating parameters based on Khakasvzryvprom CJSC

The evaluation of the roller cone bit drilling control efficiency to the integrated indicator with account of optimization criteria, with the intelligent control system and an adaptive element used, allows determining the minimum cost of the process with provision for optimum operating parameters.

CONCLUSION

Based on the calculations, it can be concluded that when drilling rock masses of mean crevassing and bedding with the drilling rigs equipped with an adaptive rotation and feeding mechanism, the tri-cone bit life increases more than twofold. When drilling highly bedded rock masses with drilling rigs equipped with an adaptive rotation and feeding mechanism the tri-cone bit life increases by up to 65%. When drilling highly crevassed rock masses with drilling rigs equipped with an adaptive rotation and feeding mechanism the tri-cone bit life increases more than five-fold.
The application of these methods is essential for determining the recommended values for the correlation between the roller cone bit life and the drilling rate, which would enhance the drilling process efficiency. The values of the bit life and the drilling rate, in their turn, shall be controlled with regard for the changing rock properties.
The rock drilling process model in terms of roller cone bit remaining life has been developed. The suggested formula

have contributed to determining the optimum characteristics of the model with regard for interrelations of the operating parameters with drilling process output and bit life. The dependencies of the model optimum operating parameters, based on the axial force correction and rotation speed subject to the drilling rig technical characteristics and the rock physical and mechanical properties, have been obtained. The integrated index, providing for the evaluation of the minimum specific expenditure and capacity, makes it possible to reduce the drilling process cost by up to 17.5%.

The application of the methods set forth above as well as the allowance for the given recommendations will be extremely useful for enhancing the rock drilling process efficiency and reducing operating expenditures at optimum output in the conditions of unpredictable, changing and impact loads.

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